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(54) Title: LARGE EFFECTIVE AREA SINGLE MODE OPTICAL WAVEGUIDE

(57) Abstract

A single mode optical waveguide fiber having a core refractive index profile of at least four segments is disclosed. The main features of the core design are at least two non-adjacent core profile segments have positive Δ %; are, at least two non-adjacent segments have negative Δ %. The novel waveguide core design provides a single mode waveguide which is suitable for high rate, long regenerator spacing systems which incorporate optical amplifiers. The waveguide core structure also lends itself to the manufacture of dispersion managed waveguide fiber.

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Large Effective Area Single Mode Optical Waveguide

Background of the Invention

The invention is directed to a single mode optical waveguide fiber designed for use in long distance, high bit rate systems operating in a wavelength range of about 1500 nm to 1600 nm. In particular, the novel waveguide fiber has a large effective area, over the operating wavelength range, to reduce the non-linear optical effects which distort the telecommunication signal.

A single mode waveguide, having a large effective area, will have reduced non-linear optical effects, including self phase modulation, four wave mixing, cross phase modulation, and non-linear scattering processes. Each of these effects causes degradation of signal in high power systems.

The scattering processes, which degrade signal, are in general described by an equation containing a term $\exp(cP/A_{eff})$, where c is a constant, P is signal power, and A_{eff} is effective area. The remaining non-linear effects are described by equations which include the ratio, P/A_{eff}, as a multiplier. Thus, an increase in A_{eff} produces a decrease in the non-linear contribution to the degradation of a light signal.

The requirement in the telecommunication industry for greater information capacity over long distances, without regenerators, has led to a reevaluation of single mode fiber index profile design.

The focus of this reevaluation has been to provide optical waveguides which:

- reduce non-linear effects, such as those noted above;

- are optimized for the lower attenuation operating wavelength range around 1550 nm;

- are compatible with the gain vs. wavelength curve of optical amplifiers; and,

- retain the desirable properties of optical waveguides such as low attenuation, high strength, fatigue resistance, and bend resistance.

An additional requirement, specifically directed to reducing four wave mixing, may be to place the zero dispersion wavelength of the waveguide fiber outside the operating window.

Previous studies, such as that disclosed in U. S. patent application S. N. 08/378,780, have started from the basic concepts of segmented core design first introduced in U. S. 4,715,679, Bhagavatula. Larger effective area waveguides were discovered for a class of core designs disclosed in the S. N. 08/378,780 cited above. A particular design incorporating at least one core region having a minimum index below that of the clad was disclosed in that application.

Using these keys, the model, which predicts properties for segmented core designs, was used to generate a family of core designs having an A_{eff}, and a mode power distribution (or electric field intensity distribution) which characterizes waveguide fiber suitable for use in the very highest performance telecommunications systems. A provisional application was mailed 9 November 95 directed to this new family of large effective area waveguides.

This application is an extension of the work disclosed in application S. N. 08/378,780 and the provisional application mailed 9 November 1995.

The particular feature of the novel family of profile designs of this application is that large effective area is combined with a total dispersion slope near zero over a selected operating wavelength range. This combination provides reduced non-linear signal degradation because of the increased effective area, as well as, reduced linear dispersion over the selected wavelength range.

Definitions

- The effective area is

$$A_{eff} = 2\pi (\int E^2 r\, dr)^2/(\int E^4 r\, dr),$$ where the integration limits are 0 to ∞, and E is the electric field associated with the propagated light.

An effective diameter, D_{eff}, may be defined as,

$$D_{eff} = 2(A_{eff}/\pi)^{1/2}.$$

- The mode field area A_{mf} is $\pi (D_{mf}/2)^2$, where D_{mf} is the mode field diameter measured using the Peterman II method wherein, $2w = D_{mf}$ and $w^2 = (2 \int E^2 r\, dr / \int [dE/dr]^2 r\, dr)$, the integral limits being 0 to infinity.

- An alpha profile is,

$$n = n_o(1 - \Delta(r/a)^{\alpha}),$$ where n_o is the greatest refractive index of the alpha index profile, Δ is defined below, r is radius, and a is the radius measured from the first to the last point of the alpha index profile. One may chose r to be zero at the n_o point of the alpha index profile or the first point of the profile may be translated a selected distance from the waveguide centerline. An alpha profile having alpha equal to 1 is triangular. When alpha is two the index profile is a parabola. As the value of alpha becomes greater than 2 and approaches about 6, the index profile becomes more nearly a step index profile. A true step index profile is described by an alpha of infinity, but an alpha of about 4 to 6 is a step index profile for practical purposes.

- The width of an index profile segment is the distance between two vertical lines drawn from the respective beginning and ending points of the index profile to the horizontal axis of the chart of refractive index vs. radius.

- The % index delta is

$$\% \Delta = [(n_1^2 - n_c^2)/2n_1^2] \times 100,$$ where n_1 is a core index and n_c is the clad index. Unless otherwise stated, n_1 is the maximum refractive index in the core region characterized by a % Δ.

- The zero reference for refractive index is chosen as the minimum refractive index in the clad glass layer. A region of refractive index in the core which is less than this minimum value is assigned a negative value.

- A refractive index profile in general has an associated effective refractive index profile which is different in shape. An effective refractive index profile may be substituted, for its associated refractive index profile without altering the waveguide performance. See reference, Single Mode Fiber Optics, Marcel Dekker Inc., Luc B. Jeunhomme, 1990, page 32, section 1.3.2.

- Bend performance is defined by a standard testing procedure in which the attenuation induced by winding a waveguide fiber about a mandrel is measured. The standard test is a measurement of induced attenuation caused in a waveguide fiber by a bend formed by one turn of fiber about a 32 mm mandrel and bends formed by 100 turns about a 75 mm mandrel. The maximum allowed bending induced attenuation is usually specified in the operating window around 1300 nm and around 1550 nm.

- An alternative bend test is the pin array bend test which is used to compare relative resistance of waveguide fiber to bending. To perform this test, attenuation loss is measured for a waveguide fiber with essentially no induced bending loss. The waveguide fiber is then woven about the pin array and attenuation again measured. The loss induced by bending is the difference between the two measured attenuations. The pin array is a set of ten cylindrical pins arranged in a single row and held in a fixed vertical position on a flat surface. The pin spacing is 5 mm, center to center. The pin diameter is 0.67 mm. During testing, sufficient tension is applied to make the waveguide fiber conform to a portion of the pin surface.

- A percent variation in Δ_i % of a refractive index profile means that any of the Δ_i % may be varied individually or in combination by the given percent.

- A percent variation in combined radius means that the change in overall core radius, Δr, is distributed proportionately among the radii of the individual core segments.

Summary of the Invention

The subject invention meets the need for a single mode optical waveguide fiber which offers the benefits of a relatively large effective area

together with a substantially flat dispersion slope, i.e., a dispersion slope having a magnitude of about 0.03 ps/nm^2-km or less, over an extended operating wavelength range.

A first aspect of the invention is a single mode waveguide having a glass core comprising at least four segments. Each segment is characterized by a refractive index profile, an outside radius, r_i, and a Δ_i %. The subscript on r and Δ refers to a particular segment. The segments are numbered 1 through n beginning with the innermost segment which includes the waveguide long axis centerline. A clad layer having a refractive index of n_c surrounds the core. The core has two non-adjacent segments each having a positive Δ %, and two additional non-adjacent segments having negative Δ %. Using this basic core configuration, a plurality of sets of Δ_i % and r_i have been found which provide for a substantially flat total dispersion curve, i.e., a curve having a slope of about 0.03 ps/nm^2-km or less, over a pre-selected wavelength range, and an effective area of at least 60 microns^2. The effective area of several core designs, having this core configuration, are greater than 70 microns^2.

A preferred embodiment of this aspect of the invention provides substantially zero dispersion slope over the wavelength range of about 1450 nm to 1580 nm. This range includes the low attenuation region around 1550 nm and the high gain wavelength range of the erbium optical amplifier.

The preferred Δ_i %'s for the two non-adjacent positive Δ % segments are in the range of about 0.1 % to 0.8 %. For the two negative Δ % segments the preferred ranges are -0.80% to -0.15%.

The preferred refractive index profile of the positive Δ % segments is chosen from the group consisting of alpha profiles, having alpha in the range of about 1 to 6, step index, rounded step index profiles, and trapezoidal profiles. The preferred refractive index profile of the negative Δ % segments is chosen from the group consisting of inverted trapezoidal, inverted step, and inverted rounded step index profiles. It is understood that in a particular profile, one negative Δ % segment may have an inverted trapezoidal shape while the other negative Δ % segment has an inverted rounded step index

shape. The number of combinations and permutations of the at least four segments refractive index profiles is quite large. Thus, for practical purposes, the search for core index profile designs which provide the required waveguide fiber properties is done using a computer model.

Dopant diffusion on centerline can cause a central index depression in the shape of an inverted cone. Also, diffusion at the location of abrupt changes in dopant concentration can produce rounding of the shoulders of a step index profile. The model is designed to take into account essentially any refractive index profile variation caused by dopant out-diffusion. A typical center diffusion depression is an inverted cone having a base radius dimension no greater than about 2 microns.

In a most preferred embodiment, segments 1 and 3 have a positive Δ % and segments 2 and 4 have a negative Δ %. As noted above, the segments are numbered sequentially beginning at 1 for the segment which includes the long axis of symmetry of the waveguide. The radii of this embodiment have limits, r_1 in the range of about 3 to 5 microns, r_2 no greater than about 10 microns, r_3 no greater than about 17 microns, and r_4 no greater than about 25 microns. The respective Δ % of the segments in this embodiment have limits, Δ_1 % in the range of about 0.20% to 0.70%, Δ_2 % and Δ_4 % in the range of about -0.80% to -0.15%, and, Δ_3 % in the range of about 0.05% to 0.20%.

The core design model may be used in two ways:

- one may input structural parameters, i.e., the number of segments and relative location of core segments, the index profile shape of each segment, and the corresponding Δ_i % and the r_i of each segment, and calculate the waveguide parameters which are associated with the structure so described; or,

- one may input functional parameters, i.e., cut off wavelength, zero dispersion wavelength, total dispersion slope, effective area, mode field diameter, operating wavelength range, and bend induced attenuation of the waveguide, and calculate a family of structures which provide such functionality.

Thus, it is appropriate to assert a s cond aspect of the invention as a waveguide fiber having at least four segments. Two non-adjacent segments have positive Δ % and two non-adjacent segments have negative Δ %. The r_i and Δ_i % of the respective segments are chosen to provide a waveguide characterized by:

- a total dispersion slope having a magnitude of about 0.03 ps/nm^2-km or less over a wavelength range of about 1400 nm to 1575 nm;

- a zero dispersion wavelength outside the operating window, i.e, in the range of about 1200 nm to 1500 nm or greater than about 1575 nm (An upper limit is determined by the required dispersion in the operating window. For most uses an upper limit is about 1750 nm.);

- a mode field diameter greater than about 9 microns; and,

- a pin array bend induced attenuation ≤ 20 dB.

A notable property of the family of waveguides, described in this second aspect of the invention, is their ease of manufacture. In particular, the waveguides are relatively insensitive to variations in the Δ_i % of +/-3% and variations in the combined radius of +/-1%, as shown by the calculated parameters of Table 1.

These and other aspects and advantages of the novel family of core designs will be further disclosed and described with the help of the following drawings.

Brief Description of the Drawings

FIGS. 1a. and **1b**. illustrate a general shape of a four segment embodiment of the novel core index profile.

FIGS. 2a. and **2b**. are specific examples of a four segment embodiment of the novel core index profile.

FIG. 3. shows a typical total dispersion curve characteristic of the novel waveguide fiber.

FIG. 4. compares D_{eff} to MFD over a wavelength range for a subset of the novel core profile designs.

FIGS. 5a, **5b**, and **5c** show the sensitivity of the total dispersion to changes in radius or refractive index of the segments of the novel core index profile.

Detailed Description of the Invention

Communications systems which typically require 1 gigabit/s, and higher, transmission rates, together with regenerator spacing in excess of 100 km, usually make use of optical amplifier technology or wavelength division multiplexing techniques. Thus waveguide fiber manufacturers have had to design waveguides which are less susceptible to non-linear effects induced by higher power signals or by four wave mixing, which can occur in multiplexed systems. It is understood that a suitable waveguide fiber must have low linear dispersion and low attenuation as well. In addition, the waveguide fiber must display these properties over a particular extended wavelength range in order to accommodate wavelength division multiplexing.

Waveguide designs which also are relatively easy to manufacture and which permit management of dispersion are favored, because of their low cost and added flexibility. The designs described herein are well suited to a dispersion managing strategy in which the waveguide dispersion is varied along a waveguide fiber length to toggle the total dispersion between positive and negative values.

The novel segmented core design of this application displays the required properties catalogued above.

A general representation of the core refractive index profile is illustrated in **FIGS. 1a** and **1b**, which show Δ % charted vs. waveguide radius. Although **FIGS. 1a** and **1b** show only four discrete segments, it is understood that the functional requirements may be met by forming a core having more than four segments. However, embodiments having fewer segments are usually easier to manufacture and are therefore preferred.

Index profile structure characteristic of the novel waveguide fiber is shown by core segments **4** and **8**, which are non-adjacent segments having positive Δ %, and, core segments **2** and **6**, which are non-adjacent segments

having negative Δ %. The segments having positive and the negative Δ % may be separated by more than one segment. The refractive index profile associated with each segment may be adjusted to reach a core design which provides the required waveguide fiber properties.

Dashed lines **10**, **12**, and **14** show alternative refractive index profile shapes for three of the segments comprising the novel waveguide core. Outside radii **5**, **7**, **9**, and **11**, of the segments also may be varied to arrive at a core design which provides the required waveguide properties. Given the variables; number of segments, segment profile shape, segment Δ %, and radius, it is clear that the design problem is most easily addressed using a computer model. The basic elements of such a model are discussed in application S. N. 08/323,795.

FIG. 1b illustrates a variation of the novel waveguide fiber core design. In this case the segments having positive Δ %, **16** and **20** are the first and third segments. The second and fourth segments, **18** and **22**, have a negative Δ %. Lines **3** and **21**, in the respective **FIGS. 1a** and **1b**, represent the refractive index of the cladding which is used to calculate the Δ %'s characteristic of the segments.

Example 1 - Four Segment Embodiment

The chart of **FIG. 2a** is an embodiment of the novel waveguide core having the four segments, **26**, **28**, **30** and **32**. Each of the segments has a profile shape which is a rounded step. The rounding of the corners of the step profiles as well as the centerline refractive index depression **24** may be due to diffusion of dopant during manufacture of the waveguide fiber. It is possible, but often not necessary to compensate, for example, in the doping step, for such diffusion.

Referring to **FIG. 2a**, Δ_1 % of segment **26** is near 0.39 %, Δ_2 % of segment **28** is near -0.25 %, Δ_3 % of segment **30** is near 0.12 %, and Δ_4 % of segment **32** is near -0.25 %. The respective outside radius of each of the segments, beginning at the innermost segment and proceeding outward, is about 4 microns, about 6.5 microns, about 15 microns, and about 22 microns.

This core structure provides a waveguide fiber having the properties:

- mode field diameter 9 microns;
- D_{eff} 9.3 microns;
- A_{eff} 68 microns^2;
- cut off wavelength 1400 nm;
- pin array induced bend loss 20 dB; and,
- total dispersion slope $\leq$ 0.03 ps/nm^2-km.

Comparative Example 2 - Four Segment Embodiment

The chart of **FIG. 2b** is an embodiment of the novel waveguide core having the four segments, **36**, **38**, **40** and **42**. Each of the segments has a profile shape which is a rounded step. As noted above, the rounding of the corners of the step profiles as well as the centerline refractive index depression may be due to diffusion of dopant.

Referring to **FIG. 2b**, Δ_1 % of segment **36** is near 0.40 %, Δ_2 % of segment **38** is near -0.25 %, Δ_3 % of segment **40** is near 0.12 %, and Δ_4 % of segment **42** is near -0.25 %. The respective outside radius of each of the segments, beginning at the innermost segment and proceeding outward, is about 4 microns, about 6.5 microns, about 15 microns, and about 23.5 microns.

Note the structural differences between the index profile of **FIG. 2a** and that of **FIG. 2b** are substantially that the negative Δ %'s are less negative and that the overall core radius has been increased by 1 to 2 microns.

This core structure provides a waveguide fiber having the properties:

- mode field diameter 9.2 microns;
- D_{eff} 9.6 microns;
- A_{eff} 72 microns^2;
- cut off wavelength 1404 nm;
- pin array induced bend loss 12 dB; and,
- total dispersion slope $\leq$ 0.03 ps/nm^2-km.

Cut off wavelength is increased only slightly, but bend resistance is dramatically improved and A_{eff} is increased by about 6 % in the comparative

example. The structure alterations which combin to produce a waveguide having improved performance are the increase in Δ % in the negative index segments and the increase in overall radius. It is an indication of the robustness of the novel core index profile design that an increase in A_{eff} and in bend resistance can be achieved simultaneously.

The total dispersion curve, **46**, characteristic of the novel core refractive index profile design is shown in **FIG. 3**. The flattened region of the curve, **44**, spans a wavelength range from about 1400 nm to 1570 nm. Thus, in this wavelength operating range, non-linear dispersion effects are limited due to the larger effective area. Also linear dispersion is limited by maintaining low total dispersion magnitude over the operating wavelength.

An advantageous property of a subset of the novel core design is shown in **FIG. 4**. The effective diameter, **48**, is larger than the mode field diameter, **50**, over a wavelength range of at least 1200 nm to 1800 nm. The larger D_{eff} serves to limit non-linear effects by decreasing signal power per unit area. The smaller mode field diameter provides for better bend resistance because a larger fraction of the signal power is guided rather than radiated. It is this feature of the novel waveguide fiber core which limits non-linear effects and at the same time provides good power confinement within the waveguide and thus good bend resistance.

The relative insensitivity to changes in total radius of the total dispersion vs. wavelength is shown in **FIG. 5a**. Curve **54** is the reference curve for a core having a combined radius r. Curve **58** is the total dispersion curve for a waveguide fiber having a core combined radius, as defined above, 1 % greater than r. Curve **56** is the total dispersion curve for a core combined radius 1 % less than r. Note that the offset of curves **56** and **58** form reference curve **54** does not exceed about 2 ps/nm-km.

The relative insensitivity of total dispersion to changes in refractive index of any or all of the segments is shown in **FIG. 5b**. Curve **60** is the reference curve. Curves **64** and **62** are represent total dispersion for cases in which the refractive index varies by 3 % and -3 %, respectively. Here again

curves **64** and **62** do not differ from reference curve **60** by more than about 2 ps/nm-km.

Table 1. gives the mean and standard deviation of selected waveguide fiber parameters when combined radius is varied by +/-1 % and refractive index is simultaneously varied by +/-3 %. The reference profile is substantially that given in comparative example 2.

Table 1

	Mean	STD	Reference
λ_0 nm	1581.7	20	1580
D1550 ps/nm-km	-1.1	1.23	-1.0
Mode Field Dia. microns	9.15	0.19	9.2
Cut off λ nm	1470	21	1460
Bend Loss dB	21.1	7.5	12

The deviation from target values is seen to be small, which indicates the core design provides relatively stable waveguide fiber properties for the stated variations in waveguide fiber core structure.

The radius variations which produce a change in sign of total dispersion are shown in **FIG. 5c** with reference to **FIG. 5a**.
As before, the reference total dispersion curve **54**. A change in combined radius of 1.5 % gives total dispersion curve **68**. Combined radius changes of 2.5 % and 4.5 % give total dispersion curves **66** and **70**, respectively. Thus the novel core design is readily adaptable to manufacture of dispersion managed waveguide fiber. Periodic changes in radius along the fiber length will produce periodic changes in the sign of the total dispersion so that total dispersion for the entire waveguide fiber length may be essentially zero while the total dispersion magnitude at points along the waveguide fiber are non-zero. This management of total dispersion essentially eliminates four wave mixing while maintaining a very low full fiber length total dispersion.

Although particular embodiments of the invention have herein been disclosed and described, the invention is nonetheless limited only by the following claims.

What is claimed is:

1. A single mode optical waveguide fiber comprising:

a glass core, disposed symmetrically about the waveguide fiber long axis centerline, and including at least four segments, each said segment having a refractive index profile, a refractive index Δ_i %, and an outside radius r_i, where i is an integer which refers to a particular segment, the segments being sequentially numbered 1 through n beginning with 1 at the centerline;

a glass clad layer formed upon and enclosing said core, said clad layer having a refractive index n_c;

wherein, at least two non-adjacent core segments have a refractive index Δ % which is positive, and at least two non-adjacent core segments have a refractive index Δ % which is negative;

wherein the outside radius r_i and the Δ_i % of each said segment is chosen to provide a dispersion slope having a magnitude of about 0.03 ps/nm^2-km or less over a preselected wavelength range and an effective area greater than 60 microns^2.

2. The single mode optical waveguide fiber of claim 1 wherein the preselected wavelength range is about 1450 nm to 1580 nm.

3. The single mode optical waveguide fiber of claim 1 wherein said at least two segments having a positive Δ %, have a Δ % in the range of about 0.1% to 0.8% and said at least two segments having a negative Δ %, have a Δ % in the range of about -0.80% to -0.1%.

4. The single mode optical waveguide fiber of claim 1 wherein said at least two segments having a positive Δ %, have a refractive index profile chosen from the group consisting of an alpha profile, wherein alpha ranges from 1 to about 6, a step index profile, a rounded step index profile, and a trapezoidal profile, and said at least two segments having a negative Δ %,

have a refractive index profile selected form the group consisting of an inverted step index profile, an inverted rounded step profile and an inverted trapezoidal profile.

5. The singlemode optical waveguide fiber of claim 4 wherein the refractive index profile of the first segment of said glass core is characterized by a maximum refractive index n_1, spaced apart from the waveguide centerline, the refractive index profile being monotone decreasing between n_1 and the centerline, to form about the centerline an index depression substantially in the shape of an inverted cone, the inverted cone having a base radius no greater than about 2 microns.

6. The single mode optical waveguide fiber of claim 5 wherein said glass core includes four segments, and Δ_1 % and Δ_3 % are positive and Δ_2 % and Δ_4 % are negative.

7. The single mode optical waveguide fiber of claim 6 wherein r_1 is in the range of about 3 to 5 microns, r_2 is no greater than about 10 microns, r_3 is no greater than about 17 microns, and r_4 is no greater than about 25 microns, and $r_4 > r_3 > r_2 > r_1$.

8. The single mode optical waveguide of claim 7 wherein said glass core has respective Δ %, Δ_1 % in the range of about 0.20% to 0.70%, Δ_2 % in the range of about -0.80% to -0.15%, Δ_3 % in the range of about 0.05% to 0.20%, and, Δ_4 % is in the range of about -0.80% to -0.15%.

9. A single mode optical waveguide fiber comprising:

a glass core, disposed symmetrically about the waveguide fiber long axis centerline, and including at least four segments, each said segment having a refractive index profile, a refractive index Δ_i %, and an outside radius

r_i, where i is an integer which r fers to a particular segment, the segments being sequentially numbered 1 through n beginning with 1 at the centerline;

a glass clad layer formed upon and enclosing said core, said clad layer having a refractive index n_c;

wherein, at least two non-adjacent core segments have a refractive index Δ % which is positive, and at least two non-adjacent core segments have a refractive index Δ % which is negative;

wherein the outside radius r_i and the Δ_i % of each said segment is chosen to provide the functional properties;

a dispersion slope having a magnitude of about 0.03 ps/nm^2-km or less over a wavelength range of about 1400 nm to 1575 nm,

a zero dispersion wavelength outside the operating window which extends from about 1450 nm to 1580 nm,

a mode field diameter greater than about 9 microns, and

a pin array bend induced attenuation ≤ 20 dB.

10. The single mode optical wavelength of claim 9 wherein the functional properties are relatively insensitive to variation in Δ_i % of +/-3% and variation in combined radius of +/-1%.

11. The single mode fiber of claim 9 wherein the core profile is adjusted along the fiber length to allow control of total dispersion, associated with a fiber length, to a preselected value.

FIG. 1a

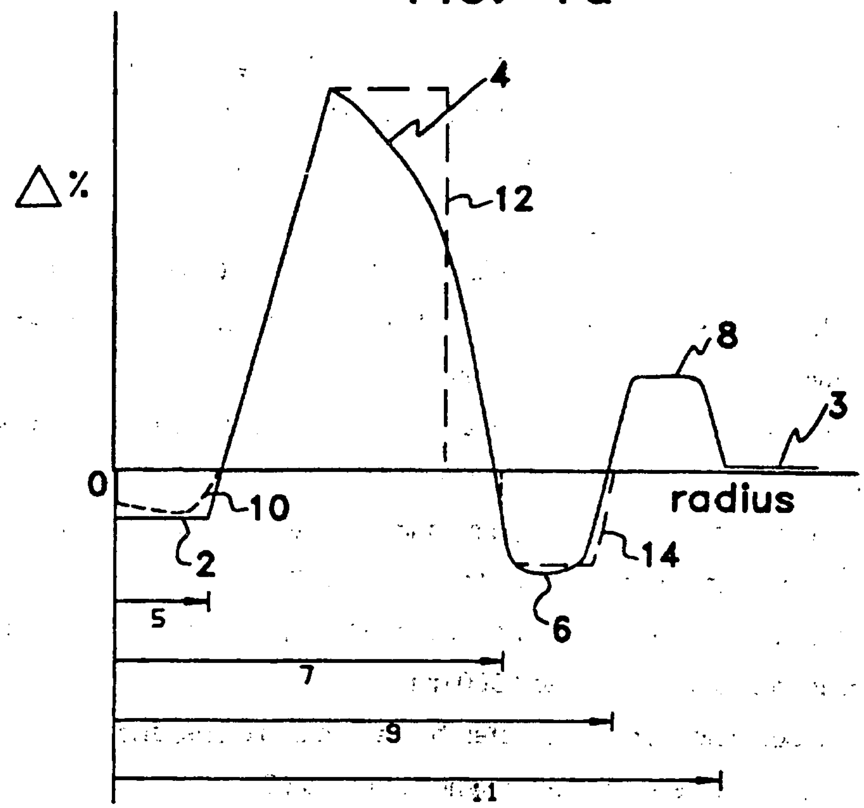


FIG. 1b

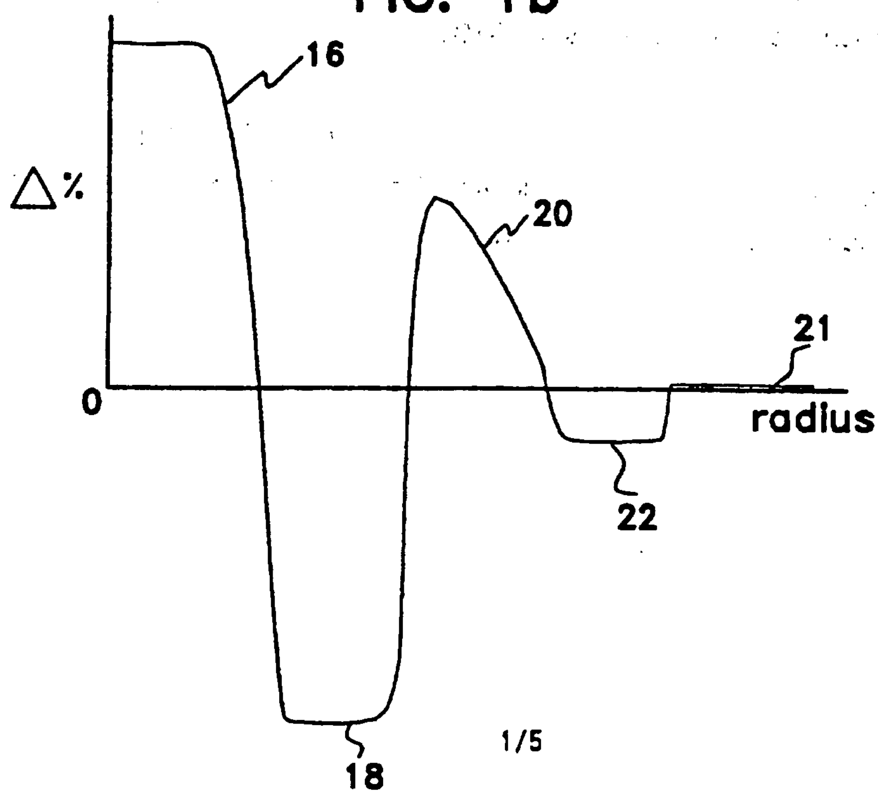
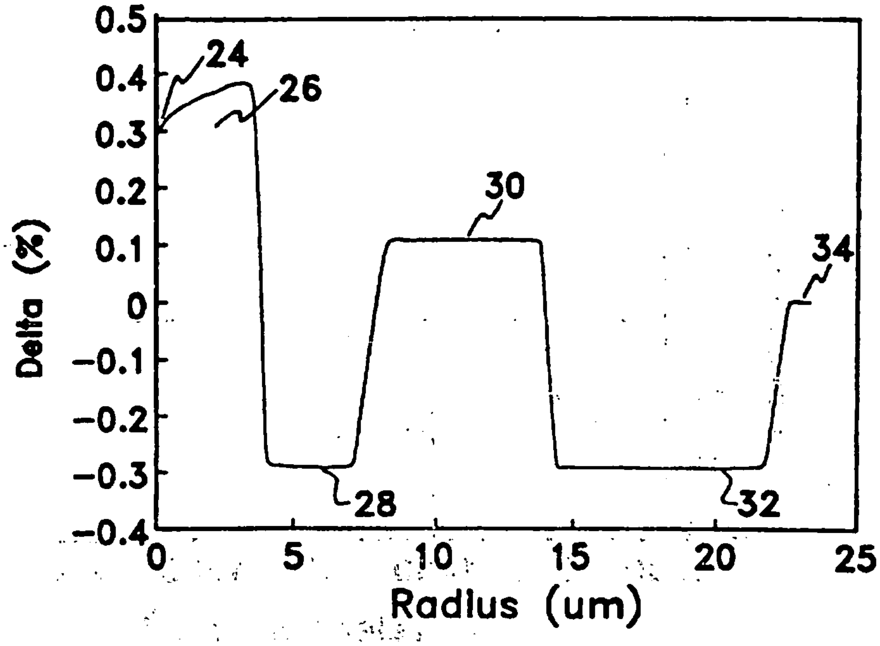


FIG. 2a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0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
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Delta (%)
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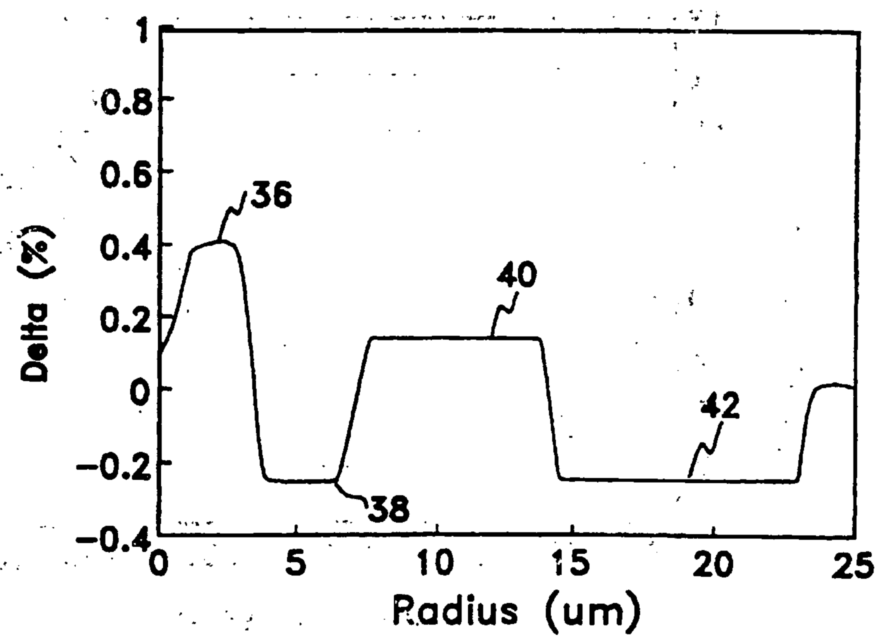
26
30
34
28
32
0
5
10
15
20
25
Radius (um)

FIG. 2b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0.8
0.6
0.4
0.2
0
-0.2
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Delta (%)
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40
42
38
0
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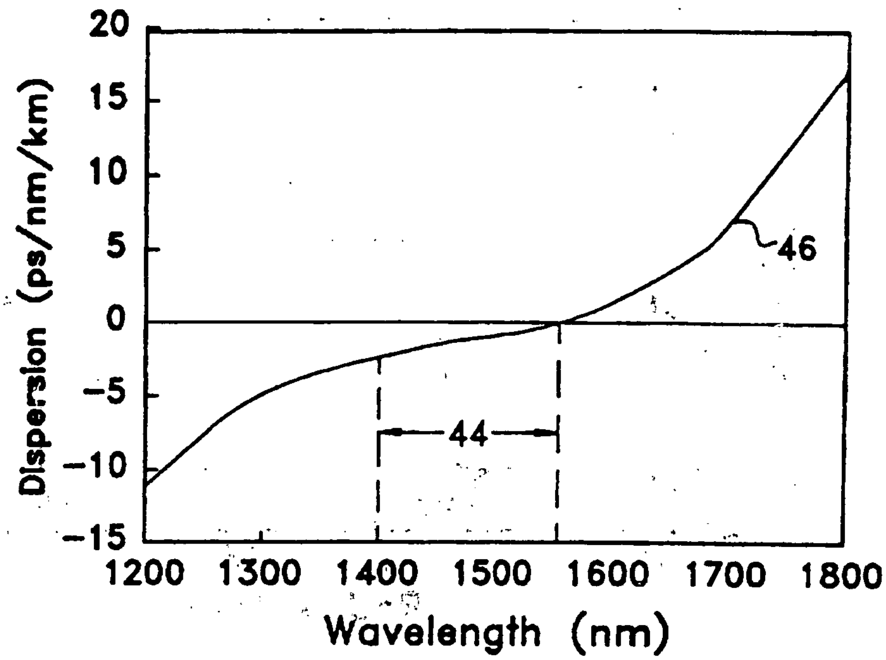
10
15
20
25
Radius (um)

FIG. 3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15
10
5
0
-5
-10
-15
Dispersion (ps/nm/km)
1200 1300 1400 1500 1600 1700 1800
Wavelength (nm)
46
44

FIG. 4

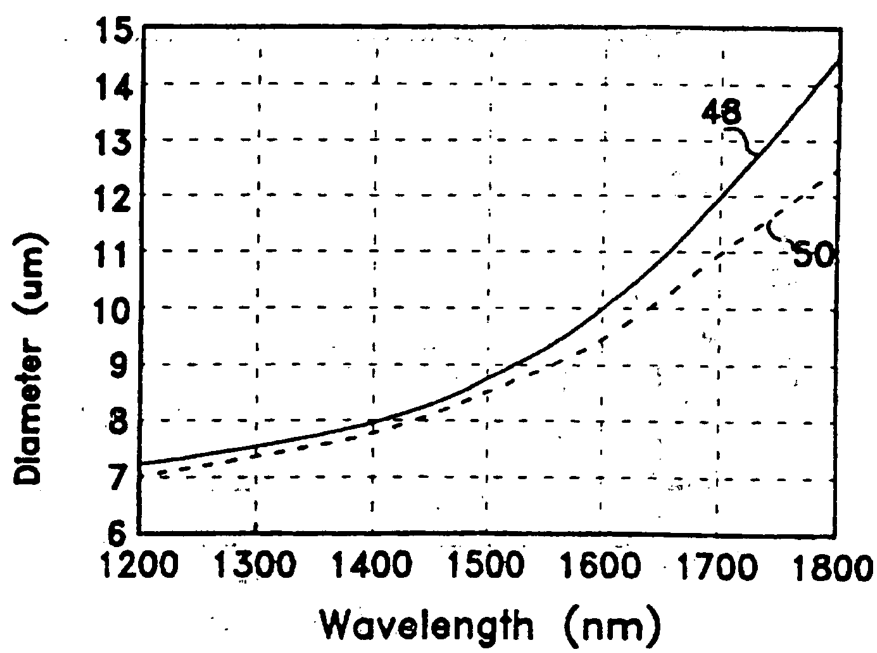

15
14
13
12
11
10
9
8
7
6
Diameter (um)
1200 1300 1400 1500 1600 1700 1800
Wavelength (nm)
48
50

FIG. 5a

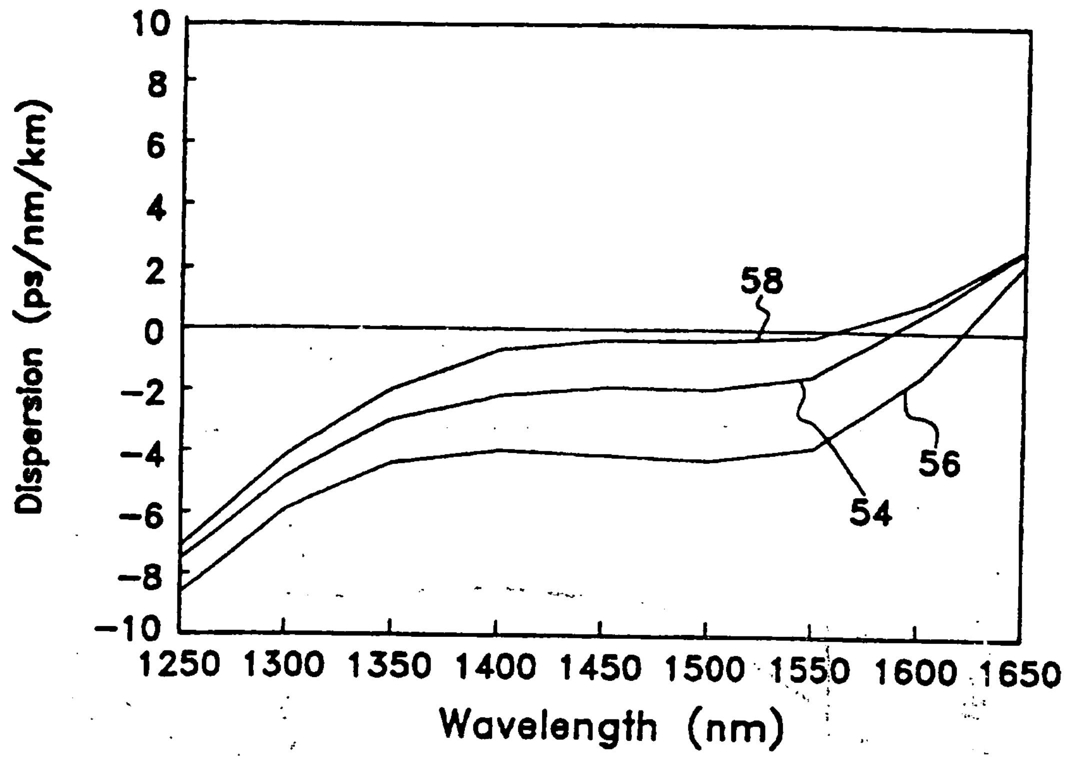

10
8
6
4
2
0
−2
−4
−6
−8
−10
Dispersion (ps/nm/km)
58
54
56
1250 1300 1350 1400 1450 1500 1550 1600 1650
Wavelength (nm)

FIG. 5b

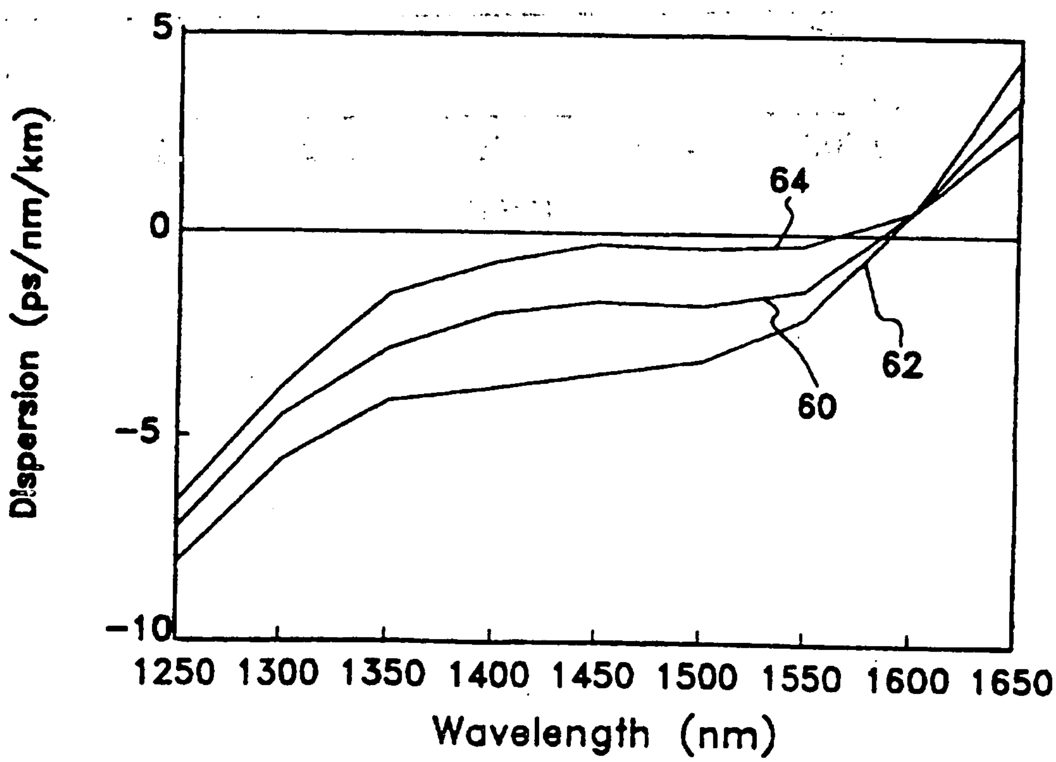
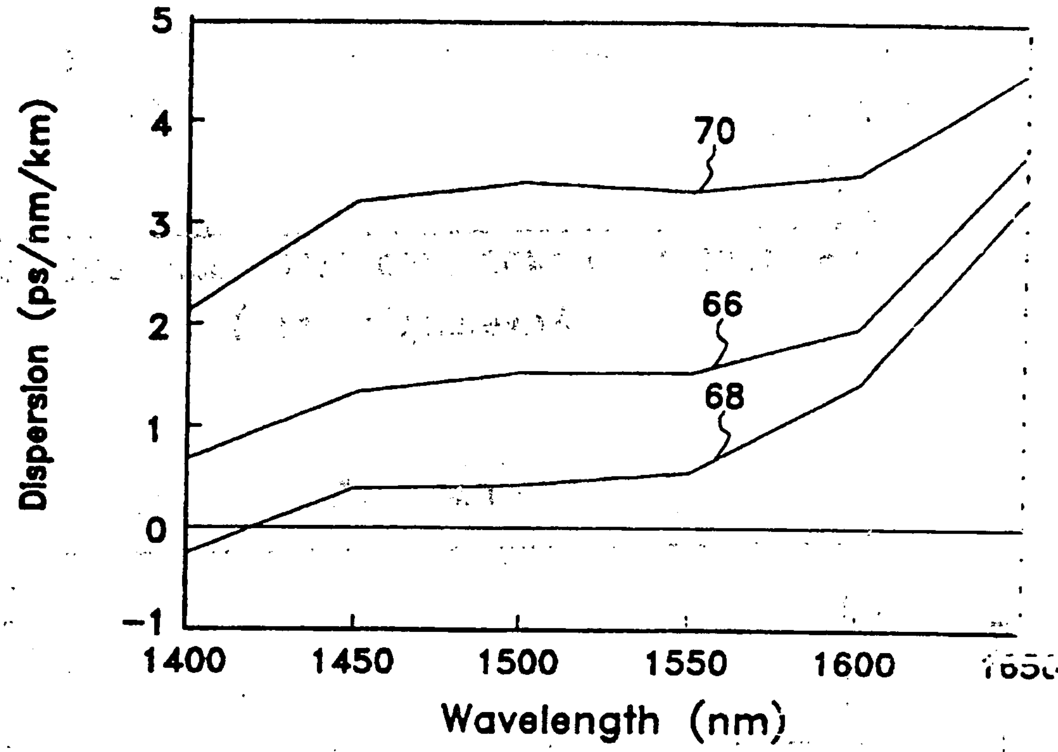

5
0
−5
−10
Dispersion (ps/nm/km)
64
60
62
1250 1300 1350 1400 1450 1500 1550 1600 1650
Wavelength (nm)

FIG. 5c


5
4
3
2
1
0
−1
Dispersion (ps/nm/km)
70
66
68
1400
1450
1500
1550
1600
Wavelength (nm)

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(54) Title: LARGE EFFECTIVE AREA SINGLE MODE OPTICAL WAVEGUIDE

(57) Abstract

A single mode optical waveguide fiber having a core refractive index profile of at least four segments (26, 28, 30, 36, 38, 40, 42) is disclosed. The main features of the core design are at least two non-adjacent core profile segments (26, 30, 36, 40) have positive Δ %: are, at least two non-adjacent segments (28, 32, 38, 42) have negative Δ %. The novel waveguide core design provides a single mode waveguide which is suitable for high rate, long regenerator spacing systems which incorporate optical amplifiers. The waveguide core structure also lends itself to the manufacture of dispersion managed waveguide fiber.

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International application No.
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Minimum documentation searched (classification system followed by classification symbols)
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Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
APS. Search terms: core, segments, dispersion.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	US 4,852,968 A (REED) 01 August 1989 (01/08/89), see the entire document.	1 and 9
A	US 4,770,492 A (LEVIN et al) 13 September 1988 (13/09/88), see the entire document.	1 and 9
A	US 5,363,463 A (KLEINERMAN) 08 November 1994 (08/11/94), see the entire document.	1 and 9

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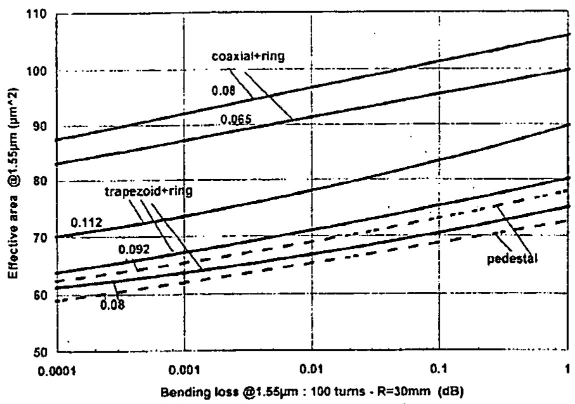


ThK3 Fig. 3. Maximum effective area as a function of computed bending loss (100 turns on a 30-mm radius mandrel) at 1.55 μm, for constant chromatic dispersion slope value shown on graph, and chromatic dispersion set at +4 ps/nm/km at 1.55 μm.

We also studied the impact of chromatic dispersion slope on effective area values for NZ-DSF (Fig. 3): pedestal, trapezoid+ring and coax profiles have larger effective areas with increased chromatic dispersion slope. The coaxial+ring profile has its maximum effective area for slopes around 0.08 ps/nm^2/km.

With an acceptable level of bending loss at 0.001 dB (100 turns on 30-mm radius mandrel), we find pedestal and trapezoid+ring index profiles yield effective areas up to 65 and 75 μm^2 respectively, if slope is allowed to increase to about 0.09 and 0.11 ps/nm^2/km. However, coaxial index profiles offer the best combination of large effective area, low bending and microbending loss, and low chromatic dispersion slope, due to their peculiar non-Gaussian field shape. With simple coaxial profile, maximum effective area is around 95 μm^2 with slope around 0.085 ps/nm^2/km. Coaxial+ring index profile allow effective area close to 90 μm^2 with slope as small as 0.065 ps/nm^2/km, value comparable to that of standard step-index fiber.

Negative dispersion fibers (−4 ps/nm/km) have effective area values smaller by about 10–15 μm^2, everything else being equal. This is due to the fact that core-cladding index differences needed to compensate for material dispersion at 1.55 μm are bigger and mode confinement is more stringent.

In summary, we have presented extensive design results regarding several well-known index profiles for NZ-DSF fibers with large effective area and quantified maximum effective area to be expected, when keeping good capability performances.

1. R.A. Saunders *et al.*, in *Optical Fiber Communication Conference*, Vol. 6 of 1997 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1997), paper WC4.
2. P. Nouchi *et al.*, in *Optical Fiber Communication Conference*, Vol. 8 of 1995 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1995), paper ThH2.
3. Y. Liu *et al.*, in *Optical Fiber Communication Conference*, Vol. 2 of 1996 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1996), paper WK15.
4. T. Kato *et al.*, in *Optical Fiber Communication Conference*, Vol. 6 of 1997 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1997), paper TuN2.
5. P. Nouchi *et al.*, in *Proceedings of the 45th International Wire and Cable Symposium*, 1996, p. 939.

Thursday

ThK4 **11:15am**

Disp rsion flattened fiber with larg -eff ctive-core ar a more than 50 μm^2

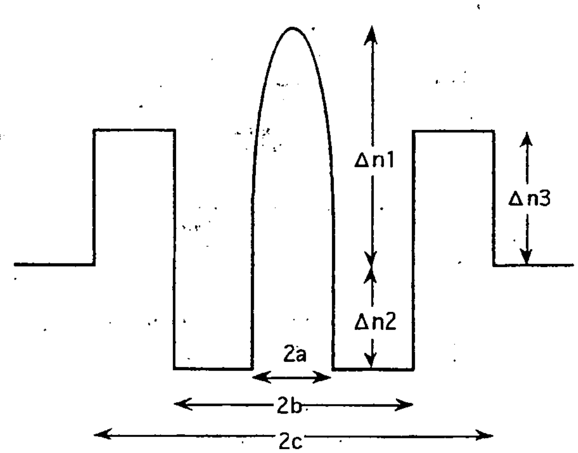
Hitoshi Hatayama, Takatoshi Kato, Masashi Onishi, Eisuke Sasaoka, Masayuki Nishimura, *Yokohama Research Laboratories, Sumitomo Electric Industries, Ltd., 1 Taya-cho, Sakae-ku, Yokohama, 244 Japan; E-mail: hatayama@yklab.sei.co.jp*

Dispersion-flattened single-mode fibers (DFFs) have been studied and developed for many years.[1] While, in the early stage, DFFs were typically designed for use in extremely wide wavelength ranges, such as 1.3–1.55 μm, the advent of erbium-doped fiber amplifier (EDFAs) has made the DFFs specifically designed for the 1.55-μm band[2,3] more important. For example, very recently, ultra high-capacity long-distance wavelength-division multiplexing (WDM) soliton transmission has been demonstrated by using DFFs.[4] Reduced dispersion variation among WDM signal channels in DFFs should be advantageous for nonsoliton WDM transmission as well.

It appears, however, that the DFFs developed so far for the above purposes usually have relatively small effective core areas or small mode field diameters (MFDs), considerably smaller than those of standard dispersion-shifted fibers. In view of nonlinear effects, it is highly desirable to enlarge the effective core area of DFFs. In this paper, newly designed 1.55-μm optimized DFFs with large-effective-core areas >50 μm^2 are proposed and demonstrated.

The refractive-index profile examined in this study is the triple cladding type[2] as illustrated in Fig. 1. There are six structural parameters to be optimized. By carefully choosing those parameters, it is possible to reduce the dispersion slope to zero around 1.55 μm. Further optimization enables the effective core area to be enlarged without significantly deteriorating the bending loss performance. Table 1 summarizes an example of such optimized designs. The calculated dispersion profile is shown in Fig. 2.

The designed DFFs have been actually fabricated by the vapor axial deposition (VAD) technique. Because the structural parameters were slightly off the design, the dispersion slope was not perfectly zero, but as small as 0.025 ps/nm^2/km (Fiber A) or 0.029 ps/nm^2/km (Fiber B) at 1.55



ThK4 Fig. 1. Schematic diagram of the refractive-index profile employing the triple-cladding structure.

ThK2 Table 2. Nonlinear Characteristics of Fabricated Fibers

	Aeff	n_2/Aeff	n_2
	μm^2	10^{-10}/W	$10^{-20}m^2$/W
	@1.55	@1.55	@1.55
Conventional DSF	48.6	7.1	3.45
Conventional DFF	32.2	10.8	3.49
LEA-NZ-DSF	80.0	3.8	3.04
LEA-NZ-DFF #1	63.6	4.2	2.67
LEA-NZ-DFF #2	67.2	4.0	2.69

Characteristics of the fabricated LEA-NZ-DFFs are shown in Table 1. Chromatic dispersion curves are shown in Figure 2. These fibers have small dispersion values from 1530–1565 nm with small dispersion slope values about 0.03 ps/nm^2/km. Attenuation loss values, which include a peculiar loss caused by depressed layer, could be lowered to 0.21 dB/km by decreasing Rayleigh scattering loss with small relative refractive-index difference of center core about 0.45%. Effective core areas are enlarged about 70 μm^2, which is twice as large as those of conventional DFFs. The n_2/Aeff values are near 4.0×10^{-10}/W, which bear comparison with those of 80-μm^2 LEA-NZ-DSFs. Such a low nonlinearity of LEA-NZ-DFFs can be explained by low n_2 values shown in Table 2.

In conclusion, by optimizing the refractive-index profile, low nonlinear dispersion-flattened fiber, which is most suitable for WDM transmission, were designed and successfully fabricated for the first time to our knowledge.

1. H. Onaka *et al.*, in *Optical Fiber Communication Conference*, Vol. 2 of 1996 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1996), paper PD19.
2. Y. Liu *et al.*, in *Optical Fiber Communication Conference*, Vol. 2 of 1996 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1996), paper WK1.
3. M. Ohashi *et al.*, in *Proceedings of European Conference on Optical Communication (ECOC'88)*, 1988, p. 445.
4. S. Kawakami and S. Nishida, Electron. Lett. **10**, 38 (1974).
5. Y. Akasaka *et al.*, in *Proceedings of European Conference on Optical Communication (ECOC'95)*, 1995, paper WE.B.2.4.

ThK3 11:00am

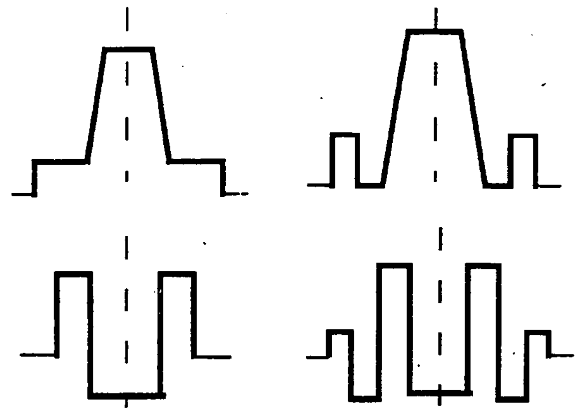
Maximum effective area for non-zero dispersion-shifted fiber

P. Nouchi, *Alcatel Cable France, 53 rue Jean Broutin, 78 700 Conflans Saint-Honorine*

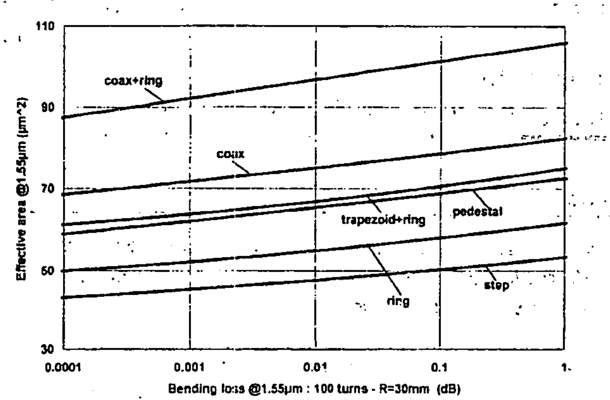
Development of wavelength-division multiplexing (WDM) systems has promoted extensive use of non-zero dispersion-shifted fiber (NZ-DSF), which is dispersion shifted but has a finite dispersion in the erbium-doped fiber amplifier (EDFA) transmission window to minimize four-wave mixing (FWM) effects. However, other nonlinear effects are still limiting systems capacities.[1] An efficient way of avoiding or reducing nonlinear effect is to increase the transmitting fiber effective area. This approach has already been widely explored for conventional DSF. For those fibers, effective areas up to 90 μm^2 have been demonstrated with various designs and processes.[2–4]

In this paper, we focus on design issues for NZ-DSF fibers with large effective areas. We quantify performances of various index-profile designs on a theoretical basis. What is the maximum possible effective area to be expected given a specific bending loss and index profile shape?

We studied several well-known index profiles: pedestal, trapezoid+ring, coaxial, coaxial+ring (Fig. 1) and simple step and ring profiles as reference data. We computed their theoretical performances according to procedure defined in Ref. 5, which has been validated for DSF design. Both positive and negative NZ-DSF were studied. Figure 2 shows an example of computed results with chromatic dispersion set at +4 ps/nm/km and slope at 0.08 ps/nm^2/km @1.55 μm (value comparable to that of standard NZ-DSF). Here, each solid curve corresponds to one profile. This type of curve allows us to 1) follow exactly how effective area is increasing when tolerance for bending loss is increasing and 2) compare capability of each profile to yield effective area within given bending loss. Same type of curves can be computed for microbending sensitivity.[5]

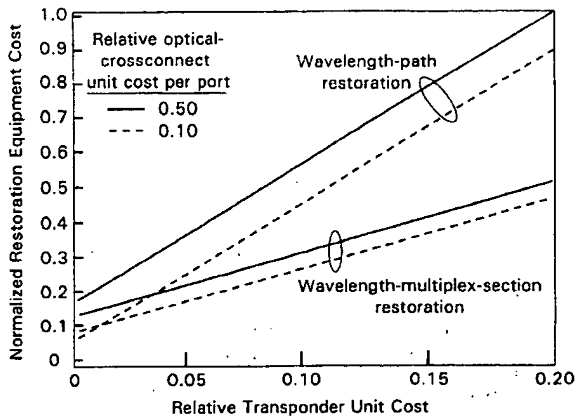


ThK3 Fig. 1. Schematic diagram of index profiles: pedestal, trapezoid+ring, coaxial, coaxial+ring.



ThK3 Fig. 2. Maximum effective area as a function of computed bending loss (100 turns on a 30-mm radius mandrel) at 1.55 μm. Chromatic dispersion is set at +4 ps/nm/km at 1.55 μm. Pedestal, trapezoid+ring, coaxial, and coaxial+ring are constant chromatic-dispersion-slope data at 0.08 ps/nm^2/km.

Thursday



ThJ5 **Fig. 3.** Normalized restoration equipment cost as a function of transponder cost. At current relative transponder unit cost (~0.4), WMS-level restoration offers large economic benefits. Should unit transponder costs decrease by an order of magnitude, this benefit becomes small.

ing from the most costly system plotted (wavelength-path restoration with unit transponder and cross-connect port costs of 0.2 and 0.5, respectively).

The results are plotted in Fig. 3. At current transponder unit costs of roughly 0.4, aggregate system cost is seen to be utterly dominated by the transponders. Thus, WMS-level restoration currently offers the promise of substantial cost advantages. However, should transponder unit costs drop by an order of magnitude, as miniaturization trends would appear to suggest, this advantage largely disappears. In this case, the operational liabilities of WMS-level restoration, alluded to earlier, would likely force its abandonment.

Given current transponder unit costs, optical restoration at the wavelength-multiplex-section level offers substantial economic benefits in national-scale, long-haul WDM mesh networks. These benefits will largely vanish, however, if transponder unit costs should decline by an order of magnitude.

1. N. Nagatsu, S. Okamoto, K. Sato, IEEE J. Sel. Areas Commun./J. Lightwave Technol. 14, (1996).

ThK 10:30–11:45am

Room A4

Optical Fibers: 2

Valeria da Silva, *Corning, Inc., Presider*

ThK1 10:30am

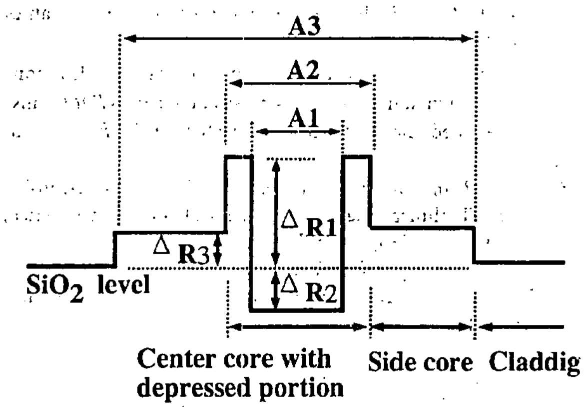
A new design for dispersion-shifted fiber with an effective core area larger than 100 μm^2 and good bending characteristics

Masao Kato, Kenji Kurokawa, Yoshiaki Miyajima, *NTT Access Network Systems Laboratories, Tokai, Ibaraki-ken, 319-11 Japan*

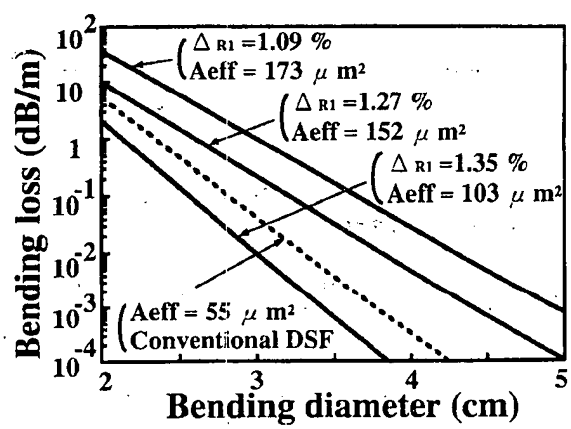
Fiber nonlinear effects could become the dominant limitations as regards system capacity and transmission distance in amplified high-capacity long-haul terrestrial and submarine transmission systems. A useful approach for reducing fiber nonlinearities is to increase the effective core area (Aeff). This leads to a higher signal power and longer repeater spacing. There have been recent reports on dispersion-shifted large-effective-area fibers with various index profiles.[1–5] They have Aeffs of 70~100 μm^2, and their bending losses are equal to or better than that of conventional step-index single-mode fiber in the 1.55-μm window.

We describe a new dispersion-shifted fiber (DSF) which has an Aeff more than double that of standard DSF and an almost identical bending loss.

Our newly designed index profile is shown schematically in Fig. 1. To enlarge the Aeff, we designed our fiber to have a center core with a fluorine-doped depressed portion and a side core. This side core has a slightly higher index than the cladding, which has the same index as pure silica. Bending loss is the main factor limiting Aeff enlargement for dispersion-shifted large-effective-area fibers, because low bending loss is important in terms of good cabling and handling capability in actual systems. To keep the bending loss low, we have adopted a side core similar to that used for conventional dual-shape core-type DSF. The side core plays an important role not only in reducing the bending loss but also in expanding the Aeff. Figure 2 shows calculated bending loss characteristics of the proposed fiber. The dotted line shows the bending loss characteristics of standard dual-shape core-type DSF (Aeff = 55 μm^2) for comparison. As shown in Fig. 2, if we



ThK1 **Fig. 1.** Schematic diagram of the index profile.



ThK1 **Fig. 2.** Calculated bending loss characteristics.

ThK1 Table 1. Measured Characteristics of the Fabricated Fiber

MFD (Mode Field Diameter),	μm	10.8
Aeff	μm^2	146
Bending Loss @2R:20mm,	dB/m	6
Zero Dispersion Wavelength,	μm	1.5
Dispersion Slope,	ps/nm²/km	0.09
PMD, (Polarization Mode Dispersion)	dB/$\sqrt{}$km	0.07

increase the refractive index difference between the center core and the cladding (Δ_{R1}) to >1.35%, it is possible to obtain an Aeff of over 100 μm^2 with almost the same low bending loss as that of standard DSF.

Our numerical calculation with six adjustable parameters provided an index profile with a large effective core area, low bending loss and low chromatic dispersion at 1.55 μm.

Table 1 shows the measured characteristics of a sample fiber that we fabricated by the modified chemical vapor deposition (MCVD) process. As shown in Table 1, it had a very large Aeff of 146 μm^2, which was almost three times as large as that of standard DSF. The bending loss was 6 dB/m measured by winding the fiber on a 20-mm diameter mandrel. This is almost as low as that of conventional DSF. The zero-dispersion wavelength shifted to around 1.5 μm shorter than we expected because of the imperfect index profile. We believe that low chromatic dispersion at 1.55 μm will be achieved by improving the fabrication technique. The chromatic dispersion slope was ~0.09 ps/nm²/km at 1.55 μm. The measured PMD value of 0.07 ps/$\sqrt{\text{km}}$ is lower than that of standard DSF.

In conclusion, we have designed a new dispersion-shifted large effective-area fiber. We have fabricated a sample fiber with an Aeff of 146 μm^2, which is almost three times as large as that of standard DSF without any deterioration in the bending loss.

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2. Y. Liu, A. Antos, M. Newhouse, in *Optical Fiber Communication Conference*, Vol. 2 of 1996 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1996), pp. 165–166.
3. S. Mahmoud and A. Kharbat, IEEE J. Lightwave Technol. 11, 1717–1720 (1993).
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5. N. Yamada, M. Sawada, A. Wada, K. Takahashi, R. Yamauchi, in *Proceedings of CLEO/PACIFIC RIM'95*, 1995, paper TuO5, p. 44.

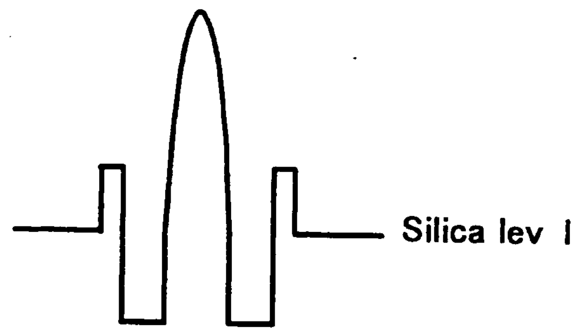
Thursday

ThK2 10:45am

Enlargement of effective core area on dispersion-flattened fiber and its low nonlinearity

Youichi Akasaka, Yoshihisa Suzuki, *Furukawa Electric Co., Ltd., 6, Yawata-kaigandori, Ichihara, Chiba 290 Japan; E-mail: akasaka@ch.furukawa.co.jp*

With an increase in information volume, a high-bit-rate transmission has been required and investigated actively.[1] As a low attenuation loss, a non-zero small dispersion, a low PMD and a low nonlinearity are expected for a fiber on a high-bit-rate transmission, large-effective-core-area non-zero dispersion-shifted fiber (LEA-NZ-DSF) was reported.[2] In addition to the above mentioned characteristics, a low dispersion dependence against a wavelength (a low dispersion slope) would be requested for wavelength-division multiplexing (WDM) transmission system. Dispersion-flattened fibers that can achieve a flat dispersion against a wavelength have been studied.[3] However, they have not been practically used yet because of their small effective core areas (about 35 μm^2) and difficulties of lowering the attenuation loss. In this report, non-zero dispersion-flattened fibers were designed and fabricated to enlarge the effective core area for the first time, to our knowledge. And the nonlinearity of these fibers were compared with those of other conventional and large-effective-core-area fibers.

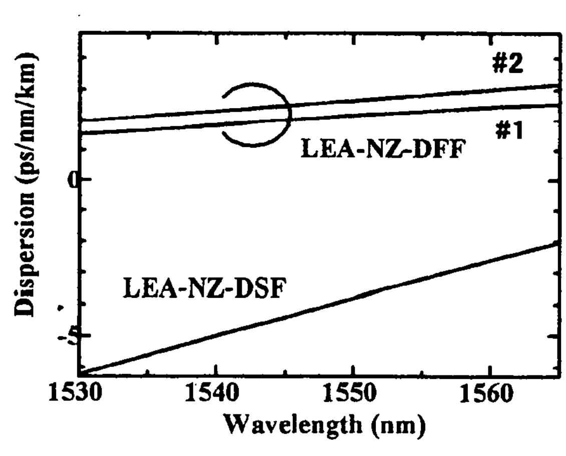


ThK2 Fig. 1. Refractive-index profile of fabricated fiber.

Dispersion flatness would be achieved with a unique waveguide-dispersion characteristic brought by a depressed cladding.[4] Effective core areas of dispersion-flattened fibers with a W-shaped index profile, which consists of a center core and a simple depressed layer, can not be enlarged because of their propagation conditions.[5] Then a segment-type refractive-index profile including the depressed layer, shown in Fig. 1, was selected for the LEA-NZ-DFF. Parameters of this profile were optimized for cut off wavelength, effective core area, dispersion values and so on.

ThK2 Table 1. Characteristics of Fabricated Fibers

	loss	λc	MFD	Aeff	Dispersion	Disp. Slope	PMD
	@1.55		@1.55	@1.55	@1.55	@1.55	avg.
	dB/km	nm	μm	μm^2	ps/nm/km	ps/nm²/km	ps/$\sqrt{}$km
#1	0.235	856	8.97	63.6	2.17	0.032	0.060
#2	0.210	830	9.12	67.2	2.66	0.035	0.061



ThK2 Fig. 2. Chromatic dispersion curves of fabricated fibers.